USES OF CKD OTHER THAN FOR FLUE GAS DESULFURIZATION

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CEMENT KILN DUST (CKD)

Introduction

The volume of by-product materials generated from core-sector industries such as cement, power, steel, and other mining and heavy industries are increasing. The cost of disposal is continuing to grow day-by-day in our society. The growth of by-product materials is inevitable unless new and beneficial use options, which are economically sound and environmentally friendly, are developed and implemented. Cement kiln dust (CKD) is a by-product material of cement manufacturing industry. It is a fine powdery material similar in appearance to portland cement. The principal constituents of CKD are compounds of lime, silica, and alumina, and iron. The physical and chemical characteristics of CKD depend on the raw materials used and the method of its collection employed at a particular cement plant. Free lime is found in CKD. The concentration of free lime is generally highest in the coarser particles of CKD captured closest to the kiln. Finer particles of CKD contain higher concentrations of sulfates and alkalis. The primary value of cement kiln dust is its cementitious property. Depending on the concentration of lime (CaO), CKD can be highly cementitious. Therefore, CKD can be used as a replacement for other cementitious materials such as portland cement, blast furnace slag cement, portland pozzolan cement, blended cements, and the like. It can also be agglomerated or palletized to produce an artificial aggregate for special applications. Due to the generally higher amounts of alkalies present, the most common beneficial use of CKD is as a stabilizing agent for wastes, for example municipal sludge, red mud, mining tailings, dredged materials, and other similar materials, where its absorptive capacity and alkaline properties reduce the moisture content, increase the bearing capacity, and provide an alkaline environment for such materials. Trace metals such as cadmium, lead, mercury, selenium, and radio-nuclides
are sometimes found in concentrations less than 0.05 percent by weight. Because some of these constituents are potentially toxic even at low concentrations, it is important to assess their levels and mobility in or leachability out of CKD before considering its use options. Some research works have been published on the use of CKD in cement-based materials. The use of CKD in cement-based composites such as concrete, dry or wet cast bricks and blocks, and controlled low-strength materials (CLSM), provides a medium where the chances of leaching out toxic elements becomes very low to negligible as the elements are bonded in a complex structure of hydrated cement paste.

**Executive Summary**

Industries such as ready-mixed concrete, precast concrete, and prestressed concrete, have provided many opportunities for the utilization of different types of industrial by-product materials. By-product materials differ vastly in their types and properties; as a result, the applicability of these materials is restricted by their suitability based on chemical and physical properties. Experience and knowledge regarding these materials vary from material to material as well as from place-to-place. In order to evaluate the potential uses of these materials, engineers, researchers, generators, and regulators need to be aware of the physical, chemical, and mineralogical properties of materials, how they can be used, and what limitations may be associated with their use. The primary value of cement kiln dust (CKD) is its cementitious property. Depending on the concentration of free lime (CaO), CKD can be highly cementitious. Therefore, it can be used as a replacement for cements. It can also be agglomerated or palletized to produce an artificial aggregate for special applications. It contains significant amount of alkalis.
The most common beneficial use of CKD is as a stabilizing agent for wastes, where its absorptive capacity and alkaline properties reduce the moisture content, increase the bearing capacity, and provide an alkaline environment for waste materials. Trace metals such as cadmium, lead, mercury, selenium, and radionuclides are generally found in concentrations less than 0.05 percent by weight. The use of CKD in cement-based composites such as concrete, bricks and blocks, and CLSM provides a medium where the chances of leaching out toxic elements becomes negligible as the elements are bonded in a complex structure of hydrated cement paste. Many other advantages of using cement kiln dust in concrete materials are as given below:

- Opens a value added use option for utilization of CKD
- Helps in sustainable development by reducing demand of new landfills
- Uniform finer particle size is useful in manufacturing of self-consolidating concrete and high-performance concrete
- Improves corrosion resistance of reinforcing steel in concrete
- Manufacturing of blended cement

The Generation of CKD

“CKD is a fine-grained solid material generated as the primary by-product of the production of cement. Cement production occurs in very large rotary kilns at high temperatures; finely ground raw material enters and rolls downward from the “cool end” of the kiln, while fuels and combustion air are introduced and drawn upward from the “hot end.” This air that is drawn into and through the kiln carries with it some of the finely ground solid raw materials, condensed fuel components, and partially reacted feed. As this air exits the cool end, the
entrained sold matter is collected before the air is vented to the atmosphere, through the large gas emission “smokestacks” that are found at all cement production facilities. CKD generation results directly from this control of particulate matter that would otherwise be discharged. In contrast to many other residues of industrial production, CKD is essentially an “off-specification” product; it much more closely resembles the raw materials entering and product leaving the operation than many other industrial solid wastes. The effective control of stack emissions at cement plants has occurred only during the past 30 years or so. Therefore, the generation of CKD as a “solid waste” in significant quantities is a relatively recent phenomenon. Nonetheless, existing stockpiles of this material are quite large at some facilities, and substantial quantities of additional CKD are generated (though not necessarily accumulated) on a continuous basis at all cement plants.” [p. 2-1 of Ref. 1].

“Cement production processes in current use in the U.S. generate CKD as an intrinsic process residue. During cement production, kiln combustion gases flow countercurrent to the raw feed and exit the kiln under the influence of induced draft fans. The rapid gas flow and continuous raw feed agitation are turbulent processes that result in large quantities of particulate matter being entrained in the combustion gases. The entrained particulate matter (as well as various precipitates) is subsequently removed from the kiln exhaust gases by air pollution control equipment; this particulate matter constitutes CKD.” [p. 3-1 of Ref. 1].

“APCDs [air pollution control devices] are used to limit dust emissions from the kiln system to the atmosphere. The combustion gases that exit the kiln consist primarily of carbon dioxide, water, fly ash (i.e., fine solid particles of ashes, dust, and soot from burning of fuels),
sulfur, and nitrogen oxides. The components of these gases are derived from the combustion of fuels, contaminants (organic and inorganic) in the kiln solids, small particles of feed and clinker material, and (for wet kilns) slurry water. After passing through the air pollution control system, the remaining combustion gases, which are discharged through a stack, consist primarily of carbon dioxide and water. Undesirable contaminants (in terms of clinker quality) may volatilize in the burning zone of the kiln and precipitate as alkalies, sulfates, and chlorine compounds to become part of the CKD” [pp. 3-2, 3 of Ref. 1].

Cement Kilns and Air Pollution

“CKD as collected is a fine-grained, solid, highly alkaline material that is generated at a temperature near 1,482°C (2,700°F). These characteristics tend to limit the types of dust collection devices that can be used to control air pollutant emissions from cement kilns. For example, because its fine-grained nature (diameter ranging from near zero micrometers or microns [µm] to greater than 50 µm) allows CKD to be easily entrained in exhaust gases, settling chambers that rely on gravity to separate particulate matter from a gas stream can only be used as a primary dust collection device to remove coarse dust particles and, in general, must be combined with more complex devices such as fabric filters (i.e., baghouses) or electrostatic precipitators. Wet scrubbers, commonly used in many mineral processing industries, cannot be used in the cement industry because adding water to the captured CKD causes it to harden ("set up") due to its cementitious properties” [p. 3-3 of Ref. 1].
CKD Gross Characteristics

“CKD is comprised of thermally unchanged raw materials, dehydrated clay, decarbonated (calcined) limestone, ash from fuel, and newly formed minerals corresponding to all stages of processing up through the formation of the clinker. An unusual feature of CKD is that, unlike typical process wastes that are substantially different than the product, CKD is essentially cement clinker that does not quite meet commercial specifications” [p. 3-25 of Ref. 1].

Physical Characteristics

“Although the relative constituent concentrations in CKD can vary significantly, CKD has certain physical characteristics that are relatively consistent. When stored fresh, CKD is a fine, dry, alkaline dust that readily absorbs water. When managed on site in a waste pile, CKD can retain these characteristics within the pile while developing an externally weathered crust, due to absorption of moisture and subsequent cementation of dust particles on the surface of the pile” [p. 3-25 of Ref. 1].

“The ability of CKD to absorb water stems from its chemically dehydrated nature, which results from the thermal treatment it receives in the kiln system. The action of absorbing water (rehydrating) releases a significant amount of heat from non-weathered dust, a phenomenon that can be exploited in beneficially using CKD. For example, CKD can be used to dewater municipal sewage sludge, while the heat of hydration can be used to sterilize the blended material” [p. 3-28 of Ref. 1].
Major, or “Bulk” Chemical Characteristics

“Although wide concentration ranges exist for most constituents, Exhibit 3-17 generally shows that the primary bulk constituents in CKD are silicates, calcium oxide, carbonates (expressed as loss of CO$_2$ and H$_2$O on ignition), potassium oxide, sulfates, chlorides, various metal oxides, and sodium oxide” [p. 3-30 of Ref. 1].

“As an additional measure of chemical characteristics, Exhibit 3-17 shows that CKD is inherently alkaline. This characteristic is a clear function of the large quantity of CaO and other alkaline compounds, such as K$_2$O, NaOH, Na$_2$CO$_3$, and Na$_2$SO$_4$, that comprise CKD. Again, however, conclusions based on process differences are tenuous using the available data. In general, the pH of CKD leachates (using standard EPA leachate procedures) falls between 11 and 13” [p. 3-30 of Ref. 1].

“Cement plants generate cement kiln dust (CKD) as a means of removing alkalies, chlorides and sulfates from the kiln system. CKD is enriched in sodium and potassium chlorides and sulfates, as well as volatile metal compounds” [p. 44 of Ref 2].

“Depending on the constituents of raw materials and the fuel, CKD is composed primarily of finely ground particles of calcium carbonate, silicon dioxide, calcium oxide, sodium, potassium chlorides and sulfates, metal oxides, portland cement hydraulic minerals, and other salts” [p. 44 of Ref.2].
“The U.S. Bureau of Mines study of CKD characteristics from 113 samples collected throughout the United States included the expected constituents of calcium, silicon, aluminum sulfur, etc. (Haynes and Kramer, 1982, IC-8885)” (Table 1) [p. 44 of Ref. 2].

**Table 1. Typical Composition of Cement Kiln Dust [p. 44 of Ref. 2]**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO(_3)</td>
<td>55.5</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>13.6</td>
</tr>
<tr>
<td>CaO</td>
<td>8.1</td>
</tr>
<tr>
<td>K(_2)SO(_4)</td>
<td>5.9</td>
</tr>
<tr>
<td>CaSO(_4)</td>
<td>5.2</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>4.5</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>2.1</td>
</tr>
<tr>
<td>KCl</td>
<td>1.4</td>
</tr>
<tr>
<td>MgO</td>
<td>1.3</td>
</tr>
<tr>
<td>Na(_2)SO(_4)</td>
<td>1.3</td>
</tr>
<tr>
<td>KF</td>
<td>0.4</td>
</tr>
<tr>
<td>Others</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Source: Bureau of Mines, IC 8885, Haynes and Kramer, 1982

“CKD satisfies this requirement and thus, having self-cementing characteristics, reacts with soil in a manner similar to Portland cement. Typically, CKD has approximately one-third of the amount of cement oxides (CaO, Al\(_2\)O\(_3\), SiO\(_2\), Fe\(_2\)O\(_3\)) present in portland cement. Of the total analytical calcium oxide shown in Table 2, approximately 6-10% represents free lime” [3].
Table 2. Analytical chemical composition of CKD, Alite and Belite [3].

<table>
<thead>
<tr>
<th>Chemical compound</th>
<th>Analysis method</th>
<th>Composition (% by weight)</th>
<th>CKDb</th>
<th>CKDc</th>
<th>Alite (C₃S)</th>
<th>Belite (C₂S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide, SiO₂</td>
<td>X-ray fluorescence</td>
<td></td>
<td>15.90</td>
<td>15.14</td>
<td>24.83</td>
<td>32.50</td>
</tr>
<tr>
<td>Aluminum oxide, Al₂O₃</td>
<td>X-ray fluorescence</td>
<td></td>
<td>3.43</td>
<td>3.91</td>
<td>1.24</td>
<td>2.13</td>
</tr>
<tr>
<td>Iron oxide, Fe₂O₃</td>
<td>X-ray fluorescence</td>
<td></td>
<td>1.90</td>
<td>1.97</td>
<td>0.94</td>
<td>1.03</td>
</tr>
<tr>
<td>Calcium oxide, CaO</td>
<td>X-ray fluorescence</td>
<td></td>
<td>43.50</td>
<td>48.40</td>
<td>72.23</td>
<td>62.83</td>
</tr>
<tr>
<td>Sulfur trioxide, SO₃</td>
<td>X-ray fluorescence</td>
<td></td>
<td>1.64</td>
<td>1.38</td>
<td>0.98</td>
<td>0.52</td>
</tr>
<tr>
<td>Sodium oxide, Na₂O</td>
<td>X-ray fluorescence</td>
<td></td>
<td>1.62</td>
<td>4.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Potassium oxide, K₂O</td>
<td>X-ray fluorescence</td>
<td></td>
<td>0.30</td>
<td>0.19</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>ASTM C575</td>
<td></td>
<td>2.94</td>
<td>2.51</td>
<td>0.14</td>
<td>0.30</td>
</tr>
<tr>
<td>Specific gravity, G</td>
<td>ASTM D 854</td>
<td></td>
<td>25.70</td>
<td>22.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hydration modulus</td>
<td>-</td>
<td></td>
<td>2.05</td>
<td>2.30</td>
<td>2.67</td>
<td>1.76</td>
</tr>
</tbody>
</table>

aHydration modulus = CaO/(Al₂O₃ + SiO₂ + Fe₂O₃).
bConducted independent of manufacturer.
cProvided by manufacturer.

“It is important to note that soluble sulfates determined by quantitative chemical analysis can be relatively high in CKD. In a separate study by the first author on dusts from three different manufacturers, soluble sulfate levels were found to vary from 2270 to 25,800 ppm. According to a study by Prakash et al [4], sulfate levels of this magnitude in a soil could potentially result in the formation of expansive minerals ettringite and thaumasite with the addition of a calcium-based stabilizer. The dust used for the study reported herein had a sulfate level of 6450 ppm, as determined by quantitative chemical analysis. Subsequent swell tests on this dust mixed with a sulfate bearing shale (1008 ppm soluble sulfate) revealed no treatment. However, the swell testing was limited in scope and additional research is needed to further investigate the potential for problematic sulfate reactions in CKD-treated soils ” [3].
Cement Production and CKD

“A typical portland cement is manufactured by feeding materials containing appropriate proportions of lime, silica, alumina and iron into the upper end of a kiln. The mix passes through the kiln at a rate controlled by the slope of the kiln and the speed at which the kiln rotates. Burning fuel is forced into the lower end of the kiln where it produces temperatures of 1400-1500 °C, changing the raw mix to a cement clinker. During this operation a small percentage of the material in the form of dust (CKD) can vary from plat-to-plant depending on the raw materials used and producing the same cement type will typically have relatively consistent composition” [5].

CKD Trace Characteristics

“Trace constituents are generally found in concentrations of less than 0.05 percent by weight and are typically expressed as milligrams per kilogram (mg/Kg), or parts per million. These constituents include certain organic chemicals, metals such as cadmium, lead, and selenium, and radionuclides. Trace constituents are important to an analysis of the chemical characteristics of CKD because some of these elements and compounds are toxic or otherwise harmful at low concentrations, and as discussed below in Chapter 5, CKD has been managed in a way that may release these trace constituents to the environment. Furthermore, the use of hazardous waste and other wastes (e.g., slag) and raw materials as fuel and raw material inputs in cement kilns has raised concerns regarding the concentrations of certain heavy metals in CKD generated by plants that use these alternative materials.” [p. 3-30 of Ref. 1].
Quantities of Cement Kiln Dust in the U.S.

“CKD is by-product of cement manufacturing and is, therefore, sometimes considered an industrial waste. Approximately 15 million tons of CKD are produced annually by the American Cement Industry [6]. A medium size cement plant may produce up to 30,000 tons of CKD annually. Most of the material is disposed off on-site without any further reuse or reclamation. In a survey that included 60% of the cement manufacturing plants in the US, it was found that due to its high alkaline content, large quantities of the cement kiln dust could not be returned to the kiln [7]” [8].

“Given the prevalence of cement manufacturing facilities across the USA, CKD represents a potentially useful and cost-effective alternative to other soil stabilizers such as lime, fly ash, and portland cement. Furthermore, recycling of CKD is an attractive alternative to landfilling. In parts of the country, CKD is being used increasingly for soil stabilization. For example, in Oklahoma CKD has been used quite extensively by some cities and counties for stabilizing road beds; however, CKD has not been fully accepted for use on the state highway system due to lack of substantial scientific proof of its effectiveness. The body of data presented in this paper lends further credibility to using CKD for soil stabilization under appropriate conditions. The focus is on the influence of soil type on the CKD effectiveness” [3].

“The Portland Cement Association estimated that 11.7 million metric tons of gross CKD (that is, CKD that is collected by air-pollution control devices) were generated in 1995 (1995 PCA CKD Survey). This is a decrease from the 12.7 million metric tons of gross CKD generated in 1990. Wide variations exist between kilns in the amount of net CKD that is generated (i.e.,
CKD that is either disposed or used beneficially off-site). Several cement plants are able to recycle all of their gross CKD back into the kiln (i.e., no net CKD produced). In 1995, the industry recycled 7.8 million metric tons of all CKD generated. EPA reported in the RTC that there is a correlation between plants that burn hazardous waste and the volume of dust that is actually disposed. Kilns that burn hazardous waste remove from the kiln system an average of 75 to 104 percent more dust per ton of clinker than kilns that do not burn hazardous waste (60 FR 7366).” [pp. 2-7 and 8 of Ref. 9].

“Net, wasted, and beneficially used CKD quantities were reported by most plants. Net CKD is the total of wasted and beneficially used CKD.” (Table 3) [p. 5 of Ref.10].

Table 3. Estimated “Net, Beneficially Used, and Waste CKD Quantities” (1995) [p. 7 of Ref. 10].

<table>
<thead>
<tr>
<th>Plants</th>
<th>Net CKD (metric tons/yr)</th>
<th>Beneficially Used CKD (metric tons/yr)</th>
<th>Wasted CKD (metric tons/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total All Companies</td>
<td>110</td>
<td>4,084,393</td>
<td>767,739</td>
</tr>
</tbody>
</table>

“Based on an extrapolation of the data supplied to EPA by respondents to the 1991 PCA Survey, which represents data from 64 percent of active U.S. cement kilns, the U.S. cement industry generated an estimated 12.9 million metric tons (14.2 million tons) of gross CKD and 4.6 million metric tons of net CKD in 1990 (Table 4). Operators of U.S. kilns recycled about 8.3 million metric tons, or 64 percent, of the gross CKD.” [p. 3-2 of Ref. 1]. “There are, however, wide variations among kilns in total gross CKD generated and gross CKD generated per ton of clinker. In addition, there are wide variations among kilns in the amount of net CKD that is generated (i.e., CKD that is either disposed or used beneficially off-site). For example, twenty-
five percent of facilities produce essentially no net CKD (CKD that is either disposed or sold), while 10 percent of the largest net generators produce almost 50 percent of all net CKD.” [p. 10-1 of Ref. 1].
Table 4. Very Rough Estimation of Quantities of Net CKD by State in 1990 Based on Clinker Production and Average Net CKD Generation Rate

<table>
<thead>
<tr>
<th>State</th>
<th>1990 Clinker Production* (million metric tons)</th>
<th>Very Rough Estimation of Net CKD** (million metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>8.83</td>
<td>0.62</td>
</tr>
<tr>
<td>Texas</td>
<td>6.99</td>
<td>0.49</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>4.27</td>
<td>0.30</td>
</tr>
<tr>
<td>Missouri</td>
<td>4.15</td>
<td>0.29</td>
</tr>
<tr>
<td>Michigan</td>
<td>3.81</td>
<td>0.27</td>
</tr>
<tr>
<td>Alabama</td>
<td>3.07</td>
<td>0.21</td>
</tr>
<tr>
<td>Indiana</td>
<td>2.72</td>
<td>0.19</td>
</tr>
<tr>
<td>New York</td>
<td>2.53</td>
<td>0.18</td>
</tr>
<tr>
<td>Iowa</td>
<td>2.49</td>
<td>0.17</td>
</tr>
<tr>
<td>South Carolina</td>
<td>2.38</td>
<td>0.17</td>
</tr>
<tr>
<td>Illinois</td>
<td>2.23</td>
<td>0.16</td>
</tr>
<tr>
<td>Florida</td>
<td>2.01</td>
<td>0.14</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>1.72</td>
<td>0.12</td>
</tr>
<tr>
<td>Maryland</td>
<td>1.64</td>
<td>0.11</td>
</tr>
<tr>
<td>Kansas</td>
<td>1.40</td>
<td>0.10</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>1.33</td>
<td>0.09</td>
</tr>
<tr>
<td>Arizona</td>
<td>1.17</td>
<td>0.08</td>
</tr>
<tr>
<td>Ohio</td>
<td>1.15</td>
<td>0.08</td>
</tr>
<tr>
<td>Virginia</td>
<td>0.97</td>
<td>0.07</td>
</tr>
<tr>
<td>Georgia</td>
<td>0.95</td>
<td>0.07</td>
</tr>
<tr>
<td>Arkansas</td>
<td>0.86</td>
<td>0.06</td>
</tr>
<tr>
<td>Utah</td>
<td>0.85</td>
<td>0.06</td>
</tr>
<tr>
<td>Colorado</td>
<td>0.84</td>
<td>0.06</td>
</tr>
<tr>
<td>Tennessee</td>
<td>0.82</td>
<td>0.06</td>
</tr>
<tr>
<td>14 other states</td>
<td>6.03</td>
<td>0.42</td>
</tr>
<tr>
<td>Totals</td>
<td>65.10</td>
<td>4.60</td>
</tr>
</tbody>
</table>

* From p. 2-6 of Ref. 1.
** Using net CKD generation rate adjusted from 0.087 to 0.07 to match the total net CKD production [pp. 3-2 and 3-17 of Ref. 1]. Actual net CKD quantities by State can be anywhere between zero to unknown (> 2) times the estimates.
Potential Uses of Cement Kiln Dust

“According to responses from the 1991 Portland Cement Association (PCA) Survey and RCRA section 3007 requests, about 780,000 metric tons (860,000 tons) of CKD were used beneficially in 1990, or 5.4 percent of the gross CKD generated in 1990, and about 19 percent of the net CKD generated for that year. This total represents 9.5 percent of the 8.2 million metric tons of CKD recycled directly back into the kiln or raw feed system in 1990. Of the 780,000 metric tons, about 71 percent (670,000 metric tons) was used for waste stabilization, 12 percent (111,000 metric tons) for soil amendment, 5.6 percent (53,000 metric tons) as liming agent, nearly three percent (25,000 metric tons) as materials additives, about one percent (11,000 metric tons) as road base, and eight percent (76,000 metric tons) for other uses.” [p. 45639 of Ref. 11].

Construction Applications

“To evaluate potential hazards of adding CKD to building materials, EPA contacted U.S. Ash, Inc. in Roanoke, VA, which purchased approximately 43 percent of all of the dust used for this purpose in 1990. U.S. Ash uses CKD to replace cement in general use concrete. Thirty percent of the cement is replaced with CKD and fly ash in equal proportions (i.e., 15 percent of the cementitious product from U.S. Ash is CKD). U.S. Ash does not purchase dust from kilns that burn hazardous waste. The dust is added in dry form to the cement, which is sold to many different customers and used in many different applications.” [p. 6-57 of Ref. 1].

“Although CKD is not typically blended into the finished cement product at the facility, CKD has been found in some construction applications to perform well when blended with cement and aggregates to make concrete. In these instances, CKD is often blended together with
other additives, such as fly ash and/or lime. The concrete made from CKD blending can be used for purposes such as road base construction. There have been a number of studies on the suitability of concrete made with CKD for this and other construction applications.” [p. 8-31 of Ref. 1].

**CKD as a Co-Blending Agent in Concrete Manufacture**

“Some of the limitations of CKD as a concrete ingredient may be overcome by incorporating additional materials, such as fly ash or slag, along with the dust. A 1980 study found that pozzolanic concrete containing CKD and fly ash had the property of autogenous healing and concluded that such concrete was potentially useful as road base and merited further development. Subsequent studies showed that the addition of either slag or fly ash to cement-CKD blends resulted in better or similar characteristics (strength, setting time, and workability) in comparison to ordinary concrete. Fly ash also reportedly acts to inhibit the expansion resulting from alkali-silica reaction. This effect might yield a higher alkali content in portland cement, allowing increased CKD recycling at applicable kilns if the ASTM standard were changed. Little information has been found on this topic.” [p. 8-33 of Ref. 1].

“Some research has moved into more commercial stages of development. For example, the U.S. Patent Office has received applications and, in some cases, issued patents for the use of various blends of CKD in concrete. Examples of patent applications include those for the following products:

- A high iron hydraulic cement manufactured from red mud and CKD by calcining them with gypsum, lime, and alumina. This composition reportedly sets rapidly, is stronger in
compression than portland cement, is more tolerant to the presence of alkali oxides, and has enhanced bonding to steel reinforcement. It is also low in cost due to the use of waste materials and the lower fusion temperature used in manufacturing;

- Cement containing blast furnace slag, CKD, and/or calcium carbonate, and optionally, gypsum. This composition is reportedly suitable as a partial replacement for portland cement, is less expensive, and forms concretes with better setting times and compressive strengths;

- A mixture of fly ash or pozzolan, CKD, aggregate, and water that, when compacted and reacted at ambient temperature, can be used as stabilized base material to underlie road surfacing. This composition reportedly minimizes the use of energy-intensive materials such as lime and asphalt; and

- A blend of portland cement, CKD, and phosphogypsum for use in producing air-filled concrete panels.

The use of CKD as a blending ingredient for concrete is apparently being actively researched and marketed. Ongoing studies of applications for CKD-blended concrete may provide new alternative uses in the future.” [pp. 8-33, 34 of Ref. 1].

**List of Beneficial Uses of CKD**

Stabilization of sludge, wastes, and contaminated soils

Soil stabilization

Land reclamation

Agricultural applications (fertilizer, liming agent)
Livestock feed ingredient

Lime-alum coagulation in water treatment

Construction applications (blending with portland cement, use as a road base material)

Sanitary landfill daily cover

Mineral filler

Lightweight aggregate

Glass making

[Sec. 8.2 of Ref. 1].

Theoretical Basis

Cement manufacturing plants generate about 30 million tons of CKD worldwide per year [12]. The US cement industry generates about 15 million tons of cement kiln dust (CKD) per year [6]. Due to high alkaline content, large quantities of CKD can’t be reused in cement manufacturing [7]. The primary value of cement kiln dust (CKD) is its cementitious property. Depending on the concentration of free lime (CaO), CKD can be highly cementitious. Because of its cementitious and alkaline properties CKD has many applications such as soil stabilization, waste treatment, soil amendment, as fertilizers and in chemical processing to recover alkali salts based on its high potassium contents, mine backfilling, glass making, coagulant in waste water treatments, and absorptive agent for oil spillages etc. [5, 7, 13 - 15]. It can also be agglomerated or palletized to produce an artificial aggregate for special applications. In Japan, an oil-absorbing artificial aggregate is reportedly manufactured using CKD, which is used to improve the rutting resistance of asphalt concrete pavements by absorbing the lighter fractions of excess asphalt cement binder during hot weather [16]. However, very few research works have been
published on the use of cement kiln dust in concrete and other cement-based products. Shoaib et al. [17] investigated the effect of cement substitution by cement kiln dust on the mechanical properties of concrete. They used three different types of cement namely, ordinary portland cement (OPC), blast furnace slag cement (BFSC), and sulfate resistant cement (SRC) in their investigation. Based on the results of mechanical properties of concrete with various content of cement substituted by CKD, Shoaib et al. [17] reported a decrease in the ultimate compressive as well as tensile strengths for OPC concrete samples with increasing percent of CKD, a slight increase in strength for BFSC, and some enhancement in concrete samples containing SRC. They have suggested that the upper limit for substitution as 30% for SRC, 20% for BFSC, and 10% for OPC. Their study suggests that direct replacement of cement by CKD is more effective for BFSC and SRC. Al-Harthy and Taha [18] studied the effect of cement by-pass dust on fresh and engineering properties of concrete where OPC was replaced between 5% and 30% by weight of cement. Based on results they have reported that substitution of cement with CKD does not lead any strength gain. However, small additions up to 10% do not seem to have a significant adverse effect on strength, especially at low water-to-cement ratios. Batis et al. [19] investigated the corrosion behavior of reinforcing steel in concrete containing CKD as a partial replacement of portland cement and concluded that replacement of portland cement with CKD lead to an increase in steel corrosion resistance. In another study on the rebars corrosion performance of different mortar specimens containing blast furnace slag and cement kiln dust simultaneously in portland cement, Batis et al. [20] have suggested that when BFS and CKD are added in proper ratio in OPC cement then the compressive strength and corrosion resistance increases. Konsta-Gdoutos et al. [21] studied the performance of cement-kiln dust-slag cement and reported that CKD provides the environment necessary to activate slag. Similar observations were also made
by Shoaib et al. [17], Konsta-Gdoutos et al. [21], further concluded that alkali concentration, fineness, and the presence of sulfate play an important role during activation and initial hydration of slag. A comparative study by Ramakrishnan [22] on the properties of concrete made with 5% blend of CKD versus the properties of corresponding concrete made with portland cement has revealed that blended cement does not adversely affect most of the hardened concrete properties. However, addition of CKD slightly retarded the setting time of cement. Nocuń-Wczelik [46] studied some properties such as setting time, strength parameters and corrosion resistance in sulfate environment of cement mortars containing from 10% to 50% of CKD by weight of cement. Based on the investigation he has reported that cement with 10% or 25% of CKD admixture meets the standard requirements and shows good corrosion resistance.

**Effect of Cement Kiln Dust (CKD) On Mortar and Concrete Mixtures**

El-Sayed et al. [23] have investigated the effect of CKD on the compressive strength of cement paste and on the corrosion behavior of embedded reinforcement. The study reported that up to 5% substitution of CKD by weight of cement had no adverse effect on cement paste strength and on the reinforcement passivity. A similar conclusion was reached in an investigation carried by Batis et al. [20]. Where it was found that when CKD and blast furnace slag are added in proper ratio in ordinary Portland cement, the compressive strength and the corrosion resistance of the mixture increases. More efficient use of CKD can be achieved through utilization of CKD as an activator for slag to create cementitious binders of superior performance [21]. Salem et al. [24] have studied the hydration of cement pastes containing granulated slag and silica fume as activated by raw CKD is relatively high as compared with
those activated by washed CKD. The reason has been attributed to the presence of excess alkali contents in raw CKD. Because of its high total lime content, CKD can also be used in lieu of lime for soil stabilization. It can be used for neutralization or pH control of agricultural soils [8].

Sorption is the result of capillary movement in the pores in the concrete which are open to the ambient medium. This mechanism is most common in buildings and is the one that will be used in this study. The sorptivity test [25] to measure the water absorption by capillary suction will be used to study the permeation properties of mortar mixed with CKD” [8].

**Research significance**

“Very few research works have been published on the use of CKD in concrete and mortar mixtures. With the increasing need to recycle industrial by-products and to protect the environment, there is a growing need to provide technical data about the performance of concrete and mortars containing CKD” [8].

1. “For most concrete mixtures, the control mix (0% CKD) produced the highest compressive strength, flexural strength and toughness values at the three water-to-binder ratios of 0.50, 0.60, and 0.70. However, concrete mixtures containing lower percentages of CKD (5%) produced close compressive strength, flexural and toughness values to the control mix, especially at a water-to-binder ratio of 0.50. This probably suggests that incorporation of low CKD contents in concrete mixtures at lower water-to-cement ratios might be as detrimental to its performance” [8].
2. “When CKD was incorporated in all mixtures while keeping the amount of cement fixed, strength of mortars was higher than the control mixture. However, it was found in the cases studied that there is no beneficial increase in strengths beyond 5% CKD addition. The sorptivity increased with the addition of CKD” [8].

**Effect of Mechanochemical Activation on Reactivity of Cement Kiln Dust-Fly Ash Systems**

**Background Material**

Through the use of cement kiln dust, cement manufacturers would be able to provide a new product to help meet the demand for cement and reduce environmental concerns regarding disposal of kiln dust and the cost associated with it.”[28]

“Experiments involving the use of cement kiln dust in concrete have been ongoing for more than 20 years. Preliminary experiments performed by many researchers focused mostly on setting time, compressive strength, flexure strength, and drying shrinkage [30, 31]. A patent was issued for the use of cement kiln dust in concrete with other mineral additives [32]. Research on setting time compressive strength, alkali-aggregate reactivity, and sulfate-related expansion has also been conducted on blends of cement, cement kiln dust, fly ash, and slag [33-37]. More recently research has been conducted on the effect of the addition of cement kiln dust on the durability of concrete, including resistance to freezing and thawing cycles, shrinkage, creep, and corrosion [19, 27, 38-39]. Despite promising results, no large-scale applications of cement kiln dust in concrete have been developed. The present research was undertaken to accomplish this goal through the use of a novel processing technique” [28].
Mechanochemical Activation

Ronin. V. studied on a method for producing cement and conducted that cement can be made highly reactive through the application of a principle known as mechanochemical, wherein particles are subjected to numerous direct impacts through mechanical grinding and the surface properties of the cement particles are modified [40]. Such impacts impart microdefects on particle surfaces increasing their surface energy and chemical reactivity [28].

The results demonstrated are for testing done on Mixture Combination I, 65% cement kiln dust and 35% fly ash. Testing was completed in mixture Combination II, 35% cement kiln dust and 65% fly ash, but the results showed that the material combination did not show any trend towards reduced set time with grinding, the hydration characteristics measured by heat of hydration testing were poor, and the compressive strength of the material decreased with increasing curing time. Therefore, only Mixture Combination I was studied in depth [28].

Cement kiln dust-fly ash paste requires a longer time to reach initial set than cement paste. Hydration reactions take place between the cement kiln dust and fly ash, however, which results in set and subsequent strength gain. Ground materials, in general, show improved reaction and strength development in comparison to simple blending [28].

Hydration, Rheology, And Strength Of Ordinary Portland Cement (OPC) - Cement Kiln Dust (CKD) – Slag Binders

“Cement kiln dust (CKD) is a fine particulate matter carried on the air streams of pulverized rock, and is collected by air pollution control equipment in the process of
manufacturing Portland cement. CKD consists mainly of partially calcined material with a chemical composition similar to cement kiln raw feed. CKD therefore has certain hydraulic and cementitious properties. Due to its fine particles, as well as its high alkali, sulfur, and chloride content, CKD often is considered to have adverse effects on the performance of concrete, including high water requirements and the risk of alkali-silica reaction” [41].

The OPC-CKD slag mixture may show increased early strength and greater corrosion resistance than OPC-CKD concrete, the OPC-CKD-slag mixture may have a lower risk of alkali-silica reaction as well. As a result, using CKD and slag together in concrete may create a cementitious system in which the individual material deficiencies will be converted into benefits” [41].

“The U.S. cement industry currently generates approximately 80% of this disposed of as landfill. Disposal of waste CKD results not only in a questionable use of land, but also in the contamination of ground water due to chemicals heavy metals in particular leaching from the material. The demand for better methods of disposing of waste CKD is increasing. One method may be to use CKD as a supplementary material in concrete; however, limited work has been done on this subject. The present study explores the hydration, rheological, and mechanical behaviors of an OPC_CKD-slag concrete, as well as a rational approach to an integrated design for mixing CKD-slag concrete” [41].

Wangs et al. studied the hydration, rheological, and mechanical behaviors of cementitious materials containing CKD, blast-furnace slag, and OPC. Experimental results indicate that:

1. “In an OPC-CKD binder system, the optimum CKD content is 15%, and the specimen made with 15% CKD has a slightly higher strength than the specimen made with pure
OPC. In an OPC-slag binder system, the optimum slag content is 25%, and the specimen made with 25% slag is 10% stronger than the specimen made with pure OPC:

2. “The alkali-silica ratio in an OPC-CKD-slag system has a profound influence on the early-age binder hydration. As the alkali-silica ratio increases, the time period for the initial binder hydrolysis (ion dissolution) is elongated, and the rate of ion dissolution increases. For a given CKD content, the major peak rate of heat evolution increases with the alkali-silica ratio of the binder; and.

3. “Rapid heat release at the very beginning of CKD hydration, together with the coarse and irregular shape of the CKD used in this study, generally results in an OPC-CKD paste with higher flow resistance than a pure OPC paste. When the CKD is incorporated with a fine slag, an OPC-CKD-slag paste generally displays stiff and viscous flow properties. Therefore, water-reducing agents or high-range water-reducing admixtures may be needed to achieve desirable flowability in OPC-CKD-slag concrete

“Due to high alkali, sulfur, and chloride contents, CKD may have adverse effects on concrete durability. More research is needed to provide further evaluation for the alkali activation and investigation on durability of OPC-CKD-slag concrete” [41].

**Influence of Soil Type on Stabilization With Cement Kiln Dust**

During the manufacture of portland cement, a large amount of dust is collected from kiln exhaust gases. While some of this cement kiln dust (CKD) is recycled, a large amount is disposed in landfills. The CKD has cementitious properties that make it an effective stabilizer for certain soil types. Miller et al. investigated the effectiveness of CKD for stabilizing low and
high plasticity soils. A tentative method based on pH measurements of soil-CKD mixtures is presented for rapidly assessing potential strength increases due to the addition of CKD [3].

**Soil stabilization with CKD**

“Previous research has shown that CKD is a potentially useful soil stabilizer. Fatani and Khan [42] utilized CKD to stabilize dune sand and asphalt mixtures used for pavement bases; they reported a 10-fold improvement in mixture stability with the addition of 11% CKD. Baghdadi et al. [5] found that CKD significantly increased the compressive strength of dune sand and that the compressive strength increased with increasing amount of CKD and curing duration [3].

“Recently a field implementation study was conducted by the FHWA at the Oklahoma PRA-CHIC12(1) Guy Study Area of the Chickasaw National Recreation Area [43]. Laboratory optimization of the CKD content for the soil on this project (PI=28) led to the use of 10% CKD, which compared to lime, resulted in an estimated cost savings of approximately $25,000 [44] for 18,000 m² of treated area. With 10% CKD the PI was reduced from 28 to 15% and the California Bearing Ratio (CBR) value was increased from slightly less than 10 (no CKD) to approximately 50. Compared to lime, the increase in CBR due to CKD was much greater; however, lime proved to be better at reducing the PI, giving a PI reduction from 28% to nearly 0% at 5% lime content. The available literature indicates that given the proper conditions, CKD can be an effective soil stabilizer. The remainder of this paper presents results of a study conducted at the University of Oklahoma to evaluate the effectiveness of CKD for stabilizing three different fine-grained soils” [3].
Cement kiln dust to soil in modest amounts has a beneficial effect on the soil behavior and is available material for stabilizing certain soil types. Based on the study presented in this section the following conclusions are made [3].

1. “Addition of CKD to soil can substantially improve the unconfined compressive strength [3].
2. “Relative to untreated soil, CKD provides some protection from the adverse effects of saturation on strength” [3].
3. “Addition of CKD rapidly increases unconfined compressive strength for 7-14 days after compaction, and thereafter more slowly” [3].
4. “Then CKD-treated soil exhibits brittle behavior during unconfined compression. Significant increases in modulus and decreases in the strain at failure occur with the addition of CKD” [3].
5. “The optimum moisture content and maximum dry unit weight, increase and decrease, respectively, with increasing amounts of CKD” [3].

References


