LITERATURE REVIEW ON CEMENT KILN DUST USAGE IN SOIL AND WASTE STABILIZATION AND EXPERIMENTAL INVESTIGATION

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ABSTRACT
The globally growing demand of cement results in towering collection of kiln dust from cement plants. The disposal of this fine dust is very difficult and poses an environmental threat. To overcome this problem, research is being carried out in different parts of the world to find out economical and efficient ways and means of using cement kiln dust (CKD) in various applications like soil stabilization, cement production, pavements, waste product stabilization, agriculture and cement products, etc. This study presents a research review on CKD usage in soil and waste utilization and the results of experimental investigation on its usage in building block manufacturing and soil stabilization.
The experimental results clearly showed that the use of 34% CKD may bring the pH of sludge above 10, which is enough to stabilize the sludge. Furthermore, the final concentrations of heavy metals were found to be within acceptable international limits. Tests conducted on blocks made using aggregates in the Eastern Province (Type-N) and light-weight pozzollanic aggregates (Type-P) indicated that addition of CKD to cement results in significant gain in strength of the blocks.

Keywords: *Cement kiln dust, soil stabilization, sewage treatment, pH, cement blocks.*

1. INTRODUCTION

Cement kiln dust (CKD) is a fine powdery material similar in appearance to Portland cement. Fresh cement kiln dusts 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]. 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 from the dust collection system (e.g., cyclone) closest to the kiln, or (2) the total quantity of dust produced can be recycled or discarded.

Large quantities of cement kiln dust are produced during the manufacture of cement clinker by the dry process. CKD contains a mixture of raw feed as well as calcined materials with some volatile salts. It is derived from the same raw materials as Portland cement but, as the CKD fraction has not been fully burnt, it differs chemically from the former. With modern manufacturing techniques, it is technically possible to introduce most CKD back into the clinker-making cycle. However, it is not done due to the restrictions on the alkali and chloride contents in the cement. The UK cement industry has estimated that over 200,000 tons a year of landfill space could be saved if the surplus CKD could be recycled into the clinker-making process or if alternative uses could be found [Aidan and Trevor 1995].

Approximately 15 million tons of CKD are produced annually by the American cement industry [Portland Cement Association 1992]. A medium size cement plant may produce up to 30,000 tons of CKD annually. Based on an analysis of existing data, including data collected by the Portland Cement Association (PCA) from operators of cement manufacturing facilities, the Agency estimates that in 1995, the cement industry had a clinker capacity of 77 million metric tons and a net CKD generation of 4.08 million metric tons which were disposed in land fills. The 1995 data indicate that 24 of the 110 cement plants (22 percent) recycle all collected dust back to the kiln, and an additional 12 plants (11%) ship all generated CKD off site for beneficial use. PCA estimates that the remaining two-thirds of cement plants (74 facilities) had a combined annual CKD land-disposal requirement of 3.3 million metric tons in 1995.

The obvious and best use of CKD is its re-incorporation in the clinker production cycle. However, this can only be done when the existing restrictions on the alkalis and chloride concentrations in cement are revised. From alkalis point of view, it is estimated that most of the CKD could be utilized in the clinker-making process if the cement alkali levels could be raised by around 0.1%. Similarly, the limits on the required chloride concentration on the performance of cement in reinforced concrete construction need to be evaluated. According to Bhatty [1995], alternative applications of CKD include agriculture - potash/lime source and animal feed; Civil engineering - fill, soil stabilization, fly ash stabilization, and blacktop filler; building materials - lightweight aggregates, blocks, low strength concrete, and masonry cement; sewage and water treatment; coagulation aid and sludge stabilization and pollution control as sulfur absorbent, waste treatment, and solidification.

The present study provides a literature review on the usage of CKD for soil and waste stabilization. The paper also includes the results of preliminary experimental investigations on CKD usage in soil and waste stabilization and building block manufacturing.

1.1 Research Review on CKD Usage for Soil Stabilization

In the field of geotechnical engineering in general and soil stabilization in particular, the parent soils are practically categorized under either cohesionless soils (i.e., sandy and larger particle-sized soils) or cohesive soils (i.e., primarily clay and silt). Since the soil stabilization mechanism of fine-grained soils requires calcium (in the form of lime) as the major stabilizing agent, it is possible that some CKDs, especially those high in free lime, would similarly be useful in stabilizing clay soils. In the case of sandy soils, which are commonly selected in the pavement layers, the usage of CKD may provide cementitious materials when it is mixed with water in a way similar to the mechanism by which Portland cements provide their binding characteristics.

Any potential application of CKD, including sand and clay stabilization, is governed by the physical and chemical composition of the dust. In practical terms, the dusts vary markedly from plant to plant in chemical, mineralogical, and physical composition, depending upon the feed raw materials, type of kiln operation, dust collection facility, and the fuel used [Klemm, 1980].

Nicholson presented a number of patents [1977, 1982] for a series of investigations on CKD and fly ash mixtures for producing subbase materials with different aggregates. CKD was used up to 16% by weight of the mixture, producing a durable mass by reacting with water at ambient temperatures. Collins and Emery [1983] demonstrated the effectiveness of substituting CKD for lime in a number of lime-fly ash-sandy aggregate systems for subbase construction. The results indicated that the majority of the CKD-treated fly ash and aggregate mixtures resulted in materials which were comparable in strength, durability, dimensional stability, and other engineering properties, to those of the conventional lime-fly ash-aggregate mixtures. Miller, et al. [1980] have also reported the use of CKD and fly ash as the cementitious ingredients in developing pozzolanic bases that demonstrated comparable properties to those of a stabilized base. It was pointed out, however, that the use of any particular CKD-fly ash combination would require an appraisal of the chemical and strength test data to establish optimum properties for a suitable mix design.

Napeierala [1983] examined the possibility of using CKD in stabilizing sandy soils for pavement subgrade applications. It was reported that an addition of 15% CKD having 5.9% free CaO and MgO, and 0.97% total alkalies (K_2O + Na_2O) ensured a compressive strength of 360 psi (2.5 MPa), which is a standard practice in Poland for the subgrade within 14 days of the treatment. Baghdadi and Rahman [1990] studied the effects of CKD on stabilizing siliceous dune sand in highway construction. It was deduced that a mix proportion of 30% CKD and 70% sand gave peak performance for application as base materials. In a somewhat similar study conducted later, Baghdadi et al. [1995] reported that the use of CKD between 12 and 50% was satisfactory to stabilize dune sand. For light applications, 12 to 30% CKD was found sufficient, and for heavily-loaded applications, about 50% CKD gave satisfactory stabilization.

A number of CKDs and clay-type soils were used by McCoy and Kriner [1971] to study the soil stabilization. Soil-CKD mixes containing 3, 8, and 10% of CKD were tested for various engineering properties, such as the unconfined compressive strength, moisture-density relationship, liquid limits (LL), plastic limit (PL), plasticity index (PI), and shrinkage limit. The study found that the use of CKD was potentially promising in stabilizing soils for subbase applications. Bhatty et al. [1996] reported that CKD with high free lime (26.6%) and moderate alkalies ($\approx$ 4.6%, expressed as Na_2O equivalent) produced mixtures with compressive strengths comparable to those obtained with cement and lime. CKDs having low free lime (0.5%) and low alkalies (2.2% Na_2O equivalent) gave lower strengths.

In general, CKDs with high free lime and moderate alkalies gave enhanced stabilization in terms of improved compressive strengths and reduced plasticity. It might also be pointed out that higher alkalies in CKDs can counter the stabilization reactions because of the ionic interference. Baghdadi [1990] reported the usage of CKD for stabilizing pure kaolinite and a 50:50 kaolinite-bentonite clay mixtures. Pure bentonite clay was highly plastic (PI $\approx$ 520), whereas the kaolinite was less plastic (PI $\approx$ 9). The 50:50 kaolinite-bentonite clay mixtures gave a PI of 150.

A study on the use of CKD in clay stabilization was also reported by Zaman et al. [1992] and Sayah [1993]. They established potentially useful correlations among the engineering properties of the clays and their stabilized counterparts. However, their investigations were based on only one CKD and primarily one clay soil, a dark grey "fat" clay, although, at times, some selected tests were also carried out on other potentially expansive clays. The primary clay used in the investigations belonged to the CH group [Spangler and Handy, 1992]. The clay-CKD mixtures containing 5% to 40% CKD by weight were cured for up to 56 days. The results showed that, with the exception of the dry densities, the engineering properties of the CKD-clay mixtures were comparable to those of fly ash-soil and cement-soil mixtures. According to Southgate and Mahboub [1994], the CBR test also positively correlates with the modulus of elasticity and strength of the stabilized soils.

CKD sharply reduced the swell potential of the clay which was expansive in nature. The swelling of the raw clay, as determined by the ASTM D 4546 procedure, dropped from over 9% to 0% when treated with 25% CKD. Meanwhile, the swell potential measured as a part of the CBR tests, dropped from nearly 9% to 0.5%. Modifications of the swelling behavior in clay properties are important when considered for pavement applications, as reduced volumetric changes imply more stable behavior in the subbase or elsewhere in the pavement structure.

Voids in the CKD-stabilized clay samples, measured optically, decreased with CKD additions. The raw clay soil had 7% void space whereas the samples with 25% CKD gave a void space between 1 and 2.3% [Sayah, 1993]. This may explain the strength gain as a consequence of decrease in voids. This phenomenon does not appear to be time dependent; it rather appears to be CKD-dosage dependent. The decrease in voids may result from a combination of processes occurring simultaneously, i.e., the hydration products developing early on, and the placement of CKD particles filling the voids to modify the morphology of the stabilized mass. Additional characterizations (scanning electron microscopy tests for example) of the CKD-treated clay samples would, however, be required to verify this point [Sayah, 1993].

CKD also increased the permeability of cohesive weathered shales giving increased coefficients of permeability from 3 x 10^{-8} to 1 x 10^{-5} cm/sec. The permeability of silty fine sand, however, somewhat decreased from 3 x 10^{-3} to 1 x 10^{-4} cm/sec when treated with 20% CKD. It might be important that if the CKD-soil mixtures were cured for longer periods, say 14 days, their permeability could decrease even further because of the growing reaction products and reduced connected voids [Todres et al., 1992]. XRD (x-ray diffraction) and SEM (scanning electron microscopy) investigations conducted on the CKD-stabilized clays showed the presence of hydration products and a subsequent decrease in void space, which resulted in increased strength and a reduction in the plasticity indices with curing times. This appears to be in line with an earlier hypothesis that CKD mechanistically functions similarly to cement [Laguros and Davidson, 1963] in stabilizing soils as it forms hydration products in the system and reduces the total porosity to promote compaction.

Azad (2000) found that an increases in the unconfined compressive strength (UCS) of soil occurred with the addition of CKD. Furthermore, the increases in UCS were inversely proportional to the plasticity index (PI) of the untreated soil. Significant PI reductions occurred with CKD treatment, particularly for high PI soils. Mohamed (2002) evaluated the potential use of cement-kiln dust (CKD) for enhancing the mechanical as well as the hydraulic properties of soils in arid lands. Various tests were conducted to determine the different physical properties of the stabilized matrix and the optimum mixture that produces maximum internal energy and minimum hydraulic conductivity was selected. The analysis showed that 6% by weight of CKD is the optimum mix design, which increases the shear strength and decreases the hydraulic conductivity to less than 10 super(-9) m/s. Therefore, the treated soil could be used as a soil-based barrier layer for containment of hazardous waste, [Mohamed 2002].

In other words, the available free lime, soluble alkalies, and fineness of CKD influence the stabilization of soil, whether the underlying stabilization process is primarily pozzolanic, or ion-exchange, or a combination of both.

1.2 Research Review on CKD Usage for Waste Treatment and Agriculture

CKD is generally non-hazardous because of its relatively low leaching properties for heavy metals. However, its presence in open atmosphere for a long period may have significant effects on the environment. Trace constituents in CKD include cadmium, lead, selenium, and radionuclide; and these constituents are generally found at concentrations of less than 0.05 percent by weight. However, since these constituents are potentially toxic, and since the composition of CKD can vary between cement plants, it is important to assess the mobility and leachability of these traces constituents in the CKD [USDOT, 1998].

Recently, the general trend all over the world is the re-utilization of the various industrial wastes or by-products, particularly the solid wastes, in useful applications in order to prevent, or at least to reduce the environmental pollution and keep the balance of the environment [Darweesh 2001]. In order to minimize the undesirable environmental impacts and to conserve materials, many researches have been conducted to investigate the beneficial use of CKD as a raw material, fertilizer, construction material, adsorbent and improving sand soil properties [El-Awady and Sami, 1997]. Optimizing soil chemistry is a critical process in agriculture. Acid soils can stunt seed germination and root development. These soils can also inhibit the uptake of nutrients by the plants [US-EPA, 2002]. The application of CKD to agricultural land can increase the pH of the soils, reduce fluctuation of pH in the soils, and as a result reduce plant and root stress. Because of its alkalinity, CKD can successfully be used as a liming agent in acidic soils [PENNSTATE, 2004].

Biosolids mixed with CKD can be recycled as agricultural amendments through direct applications to crop lands, but this practice has raised numerous environmental and health issues because of the significant concentrations of metals, organic compounds and pathogens commonly found in these waste materials [McBride *et al.,* 1997]. Once added to soils, trace metals from biosolids can be taken up by plants [Dudka and Miller, 1999]. Concentrations of trace metals in plants harvested from fields where biosolids have been applied can be substantially higher than in plants grown on unamended fields [Page *et al.*, 1987]. Trace metals applied with biosolids can also leach and contaminate surface and ground waters. In a survey of 36 sites which have received multiple applications of raw biosolids for extended periods of time, the mean levels of all trace metals Ar, Zn, Cr, Cu, Hg, Mo, Cd, Co, Ni, Pb, Se were well below the maximum permissible levels; although all metal concentrations were higher than in non-treated soils [Dudka and Miller, 1999].

Biosolids contain large amounts of easily biodegradable materials. Their application to the soil leads to a rapid decay by microorganisms and the possible release of trace metals to the soil solution for migration [Emmerich *et al.*, 1982]. The potential of trace metal migration in soil profiles is the greatest after biosolid applications [Boswell, 1975; Slide and Kardos, 1977]. Characteristics of the sludge, soil pH, soil texture, and organic matter content and quality are the factors that are particularly important with respect to the forms of trace metals and their bioavailability [Chlopecka *et al.*, 1996; Pare *et al.*, 1999]. These chemical forms of trace metals affect their solubilities, which directly influence their bioavailability [Xian, 1989].

To determine the extent to which applications of calcitic lime and sanitized biosolids affect the quality of soil organic matter (SOM), lipids extracted from an unamended soil (CON) and from soils amended with calcitic lime (CAL), and lime (LSB)- and cement kiln dust (CKD)-sanitized biosolids were characterized by chemical analysis and Pyrolysis-Gas chromatography (Py-GC) [Dinel et. el. 1999]. According to Dinel et el. [1999], the organic matter in the soil amended with CKD-treated biosolids seemed to be more biodegraded and biochemically inert than the organic matter in soils that received LSB-treated biosolids and calcitic lime and that in the control soil. The application of LSB and CKD biosolids increased the relative abundance of unsaturated aliphatics. The application of CKD-treated biosolids was more drastic than any of the other treatments and led to excessive removal by leaching and/or degradation of many lipid components and a reduction in molecular diversity. Some researchers investigated the chemical partitioning of seven trace metals in soils after one application of CKD and studied the effect on soybean during one growing season [Dinel *et al.*, 2000]. They concluded that the total concentrations of all metals, except for As in the biosolids and the CKD, were relatively low compared to the maximum concentrations of these metals in clean sludge recommended by the US Environmental Protection Agency. CKD is being used in some Canadian provinces to help maintain soil fertility. The high concentrations of calcium carbonate restore the soil's pH, acidified by fertilizers, while providing nutrients in the form of potassium and sulfur [Risdale, 1994].

Sludge stabilization is the treatment of sewage to eliminate health hazards and noxious smells. The standard UK practice is to sterilize sludge by aerobic digestion. This process is also used in USA but is meeting strong competition from lime stabilization which is proving an attractive alternative. In this process, enough lime has to be added to maintain the pH at 12.0 for two hours to achieve effective sterilization of the sewage waste [Zaman, et al., 1992]. Fresh CKD is cheaper than lime and could reduce the cost of sludge stabilization substantially, making the process a more attractive proposition, while the sludge filter cake could be a useful fertilizer. The microbiological and chemical aspects have been studied at the University of Toledo and elsewhere. Some UK companies are now using this process [Corish and Coleman, 1995].

It was also observed that upon addition of CKD to the sludge, the total heavy metal concentration of the resulting mix decreased [Bennett and Gopolan 1989]. In addition, CKD-treated sludge has a higher buffering capacity than the untreated sludge. It was concluded that alkaline treatment of sludge is not only beneficial to stabilize sludge according to US-EPA standards but is also beneficial in terms of heavy metals immobilization and minimization of metal solubility in the treated-sludge matrix [Emmerich *et al.*, 1982].

Odor has been one of the most difficult parameters to control in the processing of municipal sludge cakes. CKD treatment process was used to reduce the sludge cake odors. Mechanisms of odor control include adsorption by the tremendous surface area of CKD, pH increase, denitrification, drying the moisture of normal soil microbes, aeration and chemical elimination of hydrogen sulfide [Burnham, 1992]. According to Burnham et al. [1990 and 1992], the treatment of municipal wastewater sludge cakes with 35% CKD alone or a small amount of quicklime with 30% CKD will reduce the pathogenic microbial population present in the sludge to below the USEPA's standard. Results from a modified sludge test showed that CKD treatment renders the heavy metals present in sludge insoluble thereby minimizing their ability to enter a leachate. Cement kiln dust (CKD) was evaluated for its ability to increase the pH of acidic processed effluent in activated sludge wastewater treatment [Smith et. el. 2000]. On average, 12.8 mL of a CKD neutralizing solution (0.4625 g CKD/L distilled water) raised the pH of 100 mL of effluent from pH 6.4-7.0 to pH 8.0. The use of CKD as a neutralizing agent may be economically feasible, since the costs of adding increased phosphorus as nutrient were less than the costs associated with adding NaOH.

The treatment of waste can cover a broad range of processes, such as bulking, thickening, dewatering, stabilization and neutralization. The very fine and alkaline nature of CKD may make it suitable for some of these processes. Some wastes can be physically unstable and chemically hazardous. The adsorptive capacity and cementitious properties of CKD allow it to reduce the moisture content and increase the bearing capacity of the waste, respectively; while its alkalinity allows CKD to neutralize waste, immobilize hazardous constituents, and control residual odor [Bhatty, 1995]. CKD is a cost-effective alternative to other conventional waste treatment materials like lime and cement [University of Maine, 2002]. CKD has been used as a stabilizing and solidifying agent for environmental remediation [USDOT, 1998]. Wastes from coalmine effluent [Haynes and Kramer, 1982] and industrial wastewater, to sewage and oil sludges [Morgan et al., 1984], have been stabilized using CKD. Solidification and stabilization of oily waste with CKD have been reported in America.

Treated sewage sludge has significant organic matter content and contains macro- and micro-nutrients essential for plant growth. However, sewage sludge as well as other fertilizers and soil amendments may contain hazardous contaminants such as heavy metals. The heavy metal concentration of commercial fertilizers depends on the source material. Heavy metal concentrations decrease from highest to lowest in the following order: rock phosphate > phosphorus fertilizers > liming materials > potassium fertilizers > nitrogen fertilizers. Heavy metal concentrations in nitrogen fertilizers are very low since they are synthetic materials.

Carroll et al [1964] had studied several different types of cement dusts as a replacement of chemical fertilizer and found that they have the same ability to increase yields of alfalfa. The dust could supply plants with enough amounts of S, Mg, and K. Tamimi and Matsuyama [1972] pointed out that the application of calcium silicate to an acid soil increased dry matter yield of sorghum. Thomshiviski [1974] used the CKD as a lime potash fertilizer and found that the application of CKD for liming of acid soils improves their agrochemical fertility indices. Khader and Abu-Rub [1986] studied the possibility of using CKD as a fertilizer. However, CKD did not show any significant effect on dry matter yield of barley when planted in sand and soil mixed with CKD. Therefore, one should remember that these beneficial usages critically depend on the chemical and physical properties of the CKD.

Lafond and Simard [1999] concluded in their study that CKD can be profitably used to provide calcium to potatoes and is an efficient source of plant-available potassium comparable to commercial fertilizers without resulting in crop or soil contamination with heavy metals. Christie et al. [2001] investigated the liming and fertilizer value of alkaline-stabilized biosolids applied annually to spring barley crop. They reported that mixing with CKD produced a similar nutrient value in alkaline biosolids which is similar to inorganic fertilizer. A study carried out by Naylor and Dagneau [1985] suggested the agriculture use of CKD as a beneficial management practice. The U.S. Bureau of Mines reported that CKD contained beneficial amounts of crop micro- and macro-nutrients [Hynes and Kramer, 1982]. Thus, agriculture use of the CKD would benefit both the cement industry and agriculture. Due to its ability to hold water from 40 to 50% of its weight, CKD can assist in drought resistance [Schreiber et al. 1998].

2. EXPERIMENTAL INVESTIGATION ON CKD

Preliminary experimental studies were conducted on a CKD collected from a local cement factory. The experimental studies conducted included the determination of the chemical properties of CKD, use of CKD for soil stabilization, mineral filler gradation for CKD, use of CKD for cement concrete blocks, and Potential of CKD in sewage treatment.

2.1. Chemical Composition of CKD

A chemical analysis of the CKD, used in the experimental investigation, was carried out. The sample was fused with Lithium Metaborate and dissolved in 5% HCl and then was analyzed by ICP-AES calibrated with three levels of mixed standards prepared in LMB Blank. The sample was extracted with dilute nitric acid and analyzed for chloride with Ion Chromatography. The chemical composition of CKD is summarized in Table 1. The data in Table 1 show high concentration of alkalis and chloride. The sulfate content is within the acceptable limits [BS 8110; 2002].

Table 1. Chemical analysis of CKD.

Constituent	**Weight, %**	**Constituent**	**Weight, %**
CaO	49.3	SO_3	3.56
SiO_2	17.1	BaO (μg/g (ppm))	78.2
Chloride	6.90	Cr_2O_3	0.011
Loss on ignition	15.8	CuO	0.029
Al_2O_3	4.24	NiO	0.012
Fe_2O_3	2.89	SrO	0.37
K_2O	2.18	TiO_2	0.34
MgO	1.14	V_2O_5	0.013
Na_2O	3.84	ZnO (μg/g (ppm))	65.8
P_2O_5	0.12	ZrO_2	0.011
Equivalent alkalis ($Na_2O+0.658K_2O$)	5.27		

2.2. Evaluation of CKD Usage in Manufacturing of Bricks

To investigate the possible usage of CKD in the manufacturing of bricks, 12 different types of mortar bricks were investigated. Half of these mixes were prepared with crushed aggregates of limestone origin (Designated as Type-N). The other half were prepared with a mixture of light weight aggregate of pozzolanic origin (from Western Saudi Arabia) and limestone aggregate (Designated as Type-P). In each of the two groups of specimens, the only variable was the content of CKD addition to each mixture. Six CKD additions were used in each group (i.e. 0, 10, 20, 30, 40, and 50% by weight of cement). For each of these mixtures, three bricks were prepared and tested in compression in order to assess the effect of CKD on the compressive strength of the bricks, as per ASTM.

The percent increase in strength due to the addition of CKD in the cement block for the two types of blocks, Type-N and Type-P, are shown in Tables 2. For Type-N blocks, it can be seen that the strength of the block increases from 52% to 82% at various percentages of CKD added. For Type-P blocks, it can be seen that the strength of the block increases from 38% to about 147% at various percentages of CKD added.

Table 2. Percent Increase in Compressive Strength for Blocks of Type-N and Type-P.

Percent CKD Added	***Percent Increase in Strength****	
	Type-N	***Type-P***
10% CKD	*52.6*	*75.3*
20% CKD	*82.4*	*147.2*
30% CKD	*56.1*	*76.6*
40% CKD	*66.4*	*65.2*
50% CKD	*81.9*	*37.9*

*Compared to the strength of parent block (0% CKD)

The data in Table 2 indicates that the optimum dosage of CKD addition is 20% for both types of blocks (type N and type P). However, the improvement seems to be higher when light-weight pozzolanic aggregate was used. For this type of aggregate, the increase in strength of the blocks was about 1.5 times when 20% CKD was added to the mix. At 30% CKD, a 75% increase in strength was observed. From these preliminary results, it could be concluded that CKD may be used in the future for replacing the cement in the blocks without sacrificing the strength of the blocks.

2.3. Evaluation of CKD in the Stabilization of Sabkha and Marl Soils

As reported in the literature, CKD has been used in the stabilization of many types of soil all over the world including Saudi Arabia. In this study, four types of indigenous eastern Saudi soils, viz. sandy sabkha, white marl with low plasticity, cohesionless marl and plastic marl, were used to investigate the possibility of using CKD for stabilization. The stabilization of all the four types of soil was based on the following tests:

1. Dry density-moisture content (compaction) test according to ASTM D 1557. This test was conducted on 7 x 14 cm specimens.
2. Unconfined compression test according to ASTM D1633. This test was conducted on 7 x 14 cm specimens.

The soil stabilization program involved testing 256 specimens under compaction and another 256 specimens under unconfined compression. For each type of soil, 64 compaction and unconfined compression tests were conducted in order to determine the optimum moisture content and maximum dry density (from the compaction test) and the moisture content and maximum strength (unconfined compressive strength). The data developed is briefly discussed below in order to assess the potential of using CKD in the stabilization of indigenous soils.

All the untreated and stabilized soil specimens were cured for 14 days. Two types of curing regime were used: sealed and unsealed. The sealed specimens were prepared by wrapping the specimens in double nylon sheets directly after they were prepared in order to prevent the loss of moisture, while the unsealed ones were directly exposed to the laboratory environment after their preparation (22 ± 2 ^{o}C). After the 14 days of curing, the sealed specimens were unwrapped from the nylon sheets and tested in the unconfined compression test. All the sabkha and marl soil specimens were prepared at different moisture contents (around the optimum moisture content) in order to assess the effect of CKD and moisture content on the unconfined compression strength. Typical test results of unsealed specimens of sabkha sand stabilization for 0% and 50% CKD are presented in Table 3 and Table 4.

Table 3. Results of soil stabilization with Sabkha Sand with 0% CKD (Unsealed Specimens).

Strain (micron)	*Stress (kPa)*	*Deformation (mm)*	*Load (kg)*	*Dry Density (g/cm³)*	*Moisture content (%)*
99	*460*	*1.395*	*181*	*1.860*	*6.57*
96	*579*	*1.355*	*227*	*1.860*	*6.57*
107	*593*	*1.505*	*233*	*1.895*	*8.07*
89	*632*	*1.255*	*248*	*1.895*	*8.07*
82	*681*	*1.155*	*267*	*1.920*	*9.58*
89	*686*	*1.250*	*269*	*1.920*	*9.58*
89	*636*	*1.255*	*250*	*1.888*	*11.07*
86	*657*	*1.205*	*258*	*1.888*	*11.07*

Table 4. Results of soil stabilization with Sabkha Sand with 50% CKD (Unsealed Specimens)

Strain (micron)	*Stress (kPa)*	*Deformation (mm)*	*Load (kg)*	*Dry Density g/cm³*	*Moisture content (%)*
101	*2634*	*1.420*	*1034*	*1.659*	*10.52*
85	*2549*	*1.200*	*1001*	*1.659*	*10.52*
82	*3064*	*1.150*	*1203*	*1.682*	*12.52*
89	*3274*	*1.255*	*1285*	*1.682*	*12.52*
82	*3396*	*1.155*	*1333*	*1.716*	*14.52*
79	*3702*	*1.105*	*1453*	*1.716*	*14.52*
135	*2329*	*1.905*	*915*	*1.707*	*16.52*
125	*2269*	*1.755*	*891*	*1.707*	*16.52*

The following observations can be made from the experimental data on the sabkha soil:

- As the CKD increases from 0% to 50% by weight of soil, the maximum dry density decreased from 1.920 to 1.716 g/cm^3. Similarly, the optimum moisture content increases from 9.58% (for 0% CKD) to 14.52% (for 50% CKD).
- The unconfined compressive strength increased from 684 kPa (for 0% CKD) for the unsealed specimens to 3,870 kPa (for 30% CKD).
- For the sealed specimens, the strength increased from 214 kPa (for 0% CKD) to 2,752 kPa (for 50% CKD).

The following observations can be made from the experimental data on the low plasticity white marl:

- The maximum dry density decreased from 1.778 to 1.594 g/cm^3 for 0 to 50% CKD additions, respectively. The optimum moisture content increased from 17.10 to 22.50% for 0 to 30% CKD additions.
- The strength of unsealed specimens increased from 2,706 to 4,563 kPa for 0 to 50 CKD additions, with improvements of 1.69 times (169%). For the sealed specimens, the strength increased from 1,033 to 2,303 kPa.
- The optimum moisture content from strength perspective was either similar to or lower than that from compaction test for both the unsealed and sealed specimens.

The following observations can be made from the experimental data on plastic marl:

- Though the maximum dry density decreased from 1.661 to 1.516 g/cm^3 for 0 to 50% CKD additions, the optimum moisture content was not significantly affected (as compared with the other soils).
- The strength of unsealed specimens increased from 2,742 to 3,877 kPa for 0 to 50% CKD additions; the improvement being 1.41 times (141%). For the sealed specimens, the increase was from 715 to 2,218.
- The optimum moisture content from strength perspective followed the same trend as for the low plasticity "white" marl.

The following observations can be made from the experimental data on non-plastic marl:

- The decrease in the maximum dry density with CKD addition was marginal (from 1.968 to 1.849 g/cm^3) for 0 to 50% CKD, respectively. For the increase in the optimum moisture content, it was not existent in the range of 0 to 30% CKD. There was some increase in the optimum moisture content when the CKD increased from 30% to 50%.
- The strength of unsealed specimens increased from 2,067 to 6,398 kPa for 0 to 50% CKD additions, respectively, with a maximum percentage increase of 310%. In the case of sealed specimens, the strength increased from 357 to 4,709 kPa for the same CKD additions.
- The optimum water content from strength perspective was always less than that from compaction test for both the unsealed and sealed specimens.

2.4. Evaluation of CKD Usage in Sewage Treatment

The main objective of this experimental study was to investigate the possibility whether CKD could be utilized for agricultural purposes in a safe manner that is not harmful to the human and environment from health and safety points of view. Tests were carried out on the sludge obtained Al-Khobar Sewage Treatment Facility. The properties of dried sludge with lime and without lime were determined by prevalent laboratory techniques.

Results of the analysis for source CKD with the properties of domestic wastewater sludge are presented in Table 5. Several samples of sludge blended with different percentages of CKD were prepared. All the samples were dried under the sun for one week with the blank sludge samples (without CKD). Finally, the concentration of heavy metals and pH were determined. The results reported in the Table 5 clearly demonstrate the fact that 34% of CKD may bring the pH of sludge above 10, which is enough to stabilize the sludge. Furthermore, the final concentration of heavy metals was compared with the US-EPA, European, and Canadian standards. Results show that the final concentration of heavy metals is within the limits. The results of this study show that CKD can be use for the stabilization of domestic sludge and the stabilized sludge may be utilized for agriculture purposes.

Table 5. Summary Tests Results on Raw Sludge Mixed with CKD.

Parameters	**Properties of Source CKD**	**Properties of Domestic Sludge**	**Properties of Raw Sludge Mixed with CKD**		**Max. Allowable Pollutant Conc. Limit for Sewage Sludge for Land Application**		
		Dried (without lime)	**22%***	**34%**	**US-EPA[1]**	**European[2]**	**Canadian[2]**
Arsenic	--	--	--	--	75	--	75
Cadmium	29.7	25.63	27.9	26.92	85	40	20
Copper	46.5	173.8	161.5	131.6	4300	1750	--
Lead	278.2	66.2	118.4	142.7	740	1200	500
Mercury	1.5	5.4	4.8	3.9	57	25	5
Molybdenum	104.6	10.6	31.7	40.5	75	--	20
Nickel	23.6	31.3	30.6	31.7	420	400	180
Selenium	--	--	--	--	100	--	14
Zinc	185.1	909.3	692.7	669.4	7500	4000	1850
pH	10.85	6.81	9.87	10.18			

*Equivalent amount of lime being used at Al-Khobar wastewater treatment plant to achieve pH 12.

[!]All units are in mg/kg except pH.

[1] United States Environmental Protection Agency. (1997). 40 CFR Part 503, Standards for the use or disposal of sewage sludge, USEPA, Washington, D.C.

[2] Hutton, M. and C. de Meeus. (2001). Behalf of Environmental Resources Management, Analysis and Conclusions from Member States' Assessment of the Risk to Health and the Environment from Cadmium in Fertilizers, October 2001.

5. CONCLUSIONS

This literature search concluded that CKD is potentially useful in stabilizing a variety of soils (i.e. sandy and clayey). However, the stabilizing effect is primarily a function of the chemical composition, fineness, and addition level of the CKD as well as the type of parent soil. The following general conclusions can be made from the literature research and the experimental investigation carried out in this study:

- For sandy soils, the chemical stabilization is due to the binding characteristics of CKD in a way similar to Portland cements. Pozzolanic reaction may marginally contribute to the chemical stabilization if the sandy soils have amorphous silica or if fly ash is added to the mixture.
- For clayey soils, the mechanism of stabilization is three folds: (i) direct cementation (in the same way as for sandy soils); (ii) promotion of cation-exchange phenomenon by exchanging the sodium ions on the cleavage surfaces of the clay minerals by the calcium ions contributed by CKD; and (iii) pozzolanic reaction between the lime released by CKD and siliceous and aluminous phases in the clay minerals thereby producing secondary calcium silicate hydrates, which are the binding material in Portland cements.
- CKD with high free lime and low alkalis resulted in compact soils of improved compressive strengths. Free lime is potentially reactive and quickly hydrates to promote the stabilization reactions.
- CKDs with low free lime and high alkali CKDs adversely affect the unconfined compressive strength. Higher alkalis in CKD could counter the stabilization reactions because of the ionic interference, particularly with clayey soils.
- CKDs with low loss on ignition (LOI) and moderate alkalis reduce the plasticity index (PI) and improve the unconfined compressive strength of clay soils. In some cases, the shrinkage limits may increase to higher values than their respective optimum moisture contents.
- CKDs with high LOI and low alkali resulted in relatively lower strength and higher plasticity indices (i.e. less improvement of PIs). High LOI indicates that the CKD is high in slow-reacting calcium carbonate and low in reactive free lime.
- A moderately free lime CKD with low alkalis (though high in LOI), reduced their plastic indices, improved compressive strength and wet-dry durability, and increased maximum dry densities while reducing the optimum moisture contents.
- Though CKD improved almost all types of soil, the improvement in the unconfined compressive strength is more pronounced with low PI soils.
- The most important environmental-related uses of CKD are the fixation that is neutralization of wastes and other materials, solidification which consists of dewatering and solidification of wastes prior to landfilling. Flocculation of suspended solids in wastewater offers an economical replacement of chemical coagulant. Finally, CKD may be used as a soil conditioner and a source of nutrient to enhance crop yield.
- Tests conducted on blocks made using normal-weight aggregates (Type N) and light-weight pozzollanic aggregates (Type P) indicate that the addition of CKD to cement results in significant gain in strength of the blocks. For Type N blocks, the addition of up to 50% CKD does not result in decrease in strength of the block. Strength gain of up to 80% has been observed for these blocks.
- For Type P blocks it has been observed that strength gain up to 148% can be achieved for CKD addition of 20%. For higher CKD addition, the strength gain is significantly reduced, being 38% at 50% addition.

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