Geotechnical Properties of Some Coal Fly Ash Stabilized Southwestern Nigeria Lateritic Soils

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Abstract

This study on stabilization of tropical lateritic soils using self-cementing coal fly ash evaluated the effects of the addition of self-cementing coal fly ash on the engineering properties of three lateritic soils from southwestern Nigeria. The engineering properties investigated were those normally involved in highway design and construction. Increasing percentages (by weight of dry soil) of coal fly ash, ranging from 0% through 15% in 2.5% increments, were added and the geotechnical properties assessed. It was observed, for all the soils, that increasing coal fly ash contents brought about increasing improvements in the plasticity and mechanical properties of the soils. When comparing the average value of the properties at 0% coal ash content to their average values at 12.5% coal ash content, there was a reduction in the liquid limits (from 39.0% to 33.3%), a reduction in the plasticity indices (from 15.3% to 9.3%), a reduction in the optimum moisture contents (from 15.8% to 9.7%) accompanied by an increase in the maximum dry densities (from 1920 to 2180 kg/m^3), and an increase in the unsoaked CBR values (from 20.0% to 53.0%). For the stabilization of lateritic soils with coal fly ash, a coal fly ash of 12.5% by weight of dry soil was recommended because the improvements in the soil's properties tapered off at about that percentage of coal ash content.

Keywords: Soil stabilization, Coal fly ash, Lateritic soils, Self-cementing

1. Introduction

According to the American Coal Ash Association (2008), coal combustion products (CCP) are the materials produced when we burn coal to generate electricity. They include fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) gypsum, and other power plant byproducts. The quantities of these by-products produced annually are enormous. For example, in the USA, up to a total of 111 million metric tons of these products were produced in 2004, of which fly ash 64.3, bottom ash 25.5, boiler slag 2.0, and FGD gypsum 28.5 million metric tons (US Geological Survey, 2006). In 2007, the total had increased to 131 million metric tons (American Coal Ash Association Educational Foundation, 2010). In China, about 375 million tons of coal ash (fly ash and bottom ash) were produced in 2009 (Greenpeace, 2010). This trend is set to continue, because coal-fired power plants continue to be a major contribution to electricity production in many countries. And with present technology, there are no other large sources of energy on the horizon that would enable immediate ramp down of coal usage. Barnes and Sear (2004) gave the contribution of coal-fired electricity generation in Poland as 94.8%, South Africa 93.0%, India 78.3%, Australia 76.9%, China 76.2%, Czech Rep 66.7%, Greece 62.3% Germany 52.0%, USA 49.9%, Denmark 47.3%, and in the UK 32.9%. In Nigeria, because of the poor performance and development of hydro and thermal power plants, coal-based power plants are, and will continue to be, the backbone of Nigeria's energy engine. They currently account for about 54% of installed capacity of utilities, and projections by the (Nigerian) Energy Commission indicate that coal will fuel the power sector for at least the next three decades (Arizona-Ogwu, 2008; Sambo, 2008).

The storage of these coal combustion by-products has constituted a serious economic problem. For example, Greenpeace (2010), reported that in terms of volume, the coal ash production in China for 2009 amounts to 424 million cubic meters a year, enough to fill a standard swimming pool every two and a half minutes. It has also been a major hazard to the environment, as evidenced by the Kingston Fossil Plant coal fly ash slurry spill in Tennessee, USA in December 2008, in which about 4.2 million m^3 of coal fly ash slurry was released (Dewan, 2008), and similar incidents. To alleviate these problems, substantial parts of these by-products have been used in various applications, including, amongst others, the following: as fill material for structural applications and embankments; as aggregate in road bases, sub-bases, and pavements; as aggregate and raw material in concrete products and grout; as mineral filler in asphalt; as feed stock in the production of cement; and as an admixture in

soil modification and/or stabilization.

Coal fly ash has been immensely and widely used in this last application, for different kinds of soils, due mainly to its pozzolanic properties. Coal fly ash is an artificial pozzolan, i.e. a siliceous or siliceous/aluminous material that, when mixed with lime and water, forms a cementitious compound. Coal fly ash is the best known, and one of the most commonly used, pozzolans in the world.

Coal fly ash is a by-product of coal fired electric power plants. It is the finely-divided and powdery coal combustion product collected by electrostatic precipitators or baghouses from the flue gases (Fly Ash Resource Center, 2010). Two classes of fly ash are defined by ASTM Standard C618 - 08a (2008). These are Class F fly ash and Class C fly ash. The chief difference between these classes is the amount of calcium, silica, alumina, and iron content in the ash. The chemical properties of the fly ash are largely influenced by the chemical content of the coal burned, which in turn depends on the type of coal, which could be anthracite, bituminous or sub-bituminous coal, or lignite. Class F fly ash is produced from the burning of anthracite or bituminous coal, and is generally low in lime, usually under 15 percent, and contains a greater combination of silica, alumina and iron (greater than 70 percent) than Class C fly ash. It is siliceous and typically pozzolanic. Class C fly ash is produced from lignite or sub-bituminous coal. These types of coal produce an ash with higher lime (CaO) content (from 15 to 30 percent), which makes it calcareous and gives it some unique self-cementing characteristics. Class C fly ash therefore possesses latent hydraulic properties in addition to its pozzolanic properties, and is therefore especially useful in soil stabilization since it may not require the addition of lime.

Lateritic soils are widespread around the world, especially in the tropics. Because of their non-swelling characteristics, they are often used as imported fill material for the prepared subgrade in different kinds of road projects. In fact, in low-cost road projects in many developing countries such as Nigeria, in many instances lateritic soils are employed in the base layer, then topped with a single or double surface dressing. To enhance the durability of such roads, the lateritic soils are often stabilized, traditionally with cement, lime or bitumen, and these in combination with different admixtures (such as coal fly ash, rice husk ash, and many other industrial and agricultural by-products). However, stabilization with only coal fly ash has not been much practiced. Nigerian coal has been widely ranked as being sub-bituminous (mainly) and lignite (Akande *et.al.*, 1992; Methane to Markets, 2005; EIA, 2006; Adeleke *et al.*, 2007; Sambo, 2008), indicating the class of fly ash derived from them to be Class C. Because it possesses self-cementing properties apart from its pozzolanic properties, and because of its availability and low cost, stabilization with only Class C fly ash is worth investigating.

Much work has been done world-wide on the stabilization of soil with coal fly ash (Brown *et al.*, 1991; Indraratna *et al.*, 1991;Beeghly, 2003; Mackiewicz and Ferguson, 2005; White *et al.*, 2005; Eskioglou and Oikonomou, 2008; Sear, 2008; Brooks, 2009; Li *et al.*, 2009; Rifa'i *et al.*, 2009). However, investigations involving tropical lateritic soils are indeed few. This study aimed to address this by investigating the effect of coal fly ash stabilization on the geotechnical properties (especially those concerned with highway design and construction) of treated lateritic soils and proffering recommendations.

2. Materials and Methods

This study was conducted on soil samples taken from three different locations from three different states within the southwestern part of Nigeria. The samples were collected at a depth of about 1.5 meters below the ground surface Soil A sample was collected at km. 6+700 along the Ado-Iworoko Road in Ekiti State, Soil B sample was collected at km. 15+000 along the in Akure-Ondo Road in Ondo State, while Soil C sample was collected at km. 3+400 along the Sagamu-Ikenne Road in Ogun State. The locations all lie between latitudes 6°50'N and 7°40'N and longitudes 3°40'E and 5°20'E (see Figure 1). Geologically, the locations fall within the basement complex of southwestern Nigeria. The laterite crust over this area is a thin layer of ironstone, from about 1 to 6 meters thick, deposited within the Quaternary age (Durotoye, 1983).

After collection, the soil samples were spread out in the laboratory for two weeks for air-drying at room temperature, after which the clods were broken down and the samples well pulverized. Thereafter, employing standard procedures, the samples were tested for their classification and index properties, as well as their consistency properties. The results are shown in Table 1. The coal fly ash obtained was grayish in colour and powdery in texture. From its particle size distribution analysis, it was found that 92% of its weight passes through sieve No 200 (75μm), something that indicates the hydraulic and pozzolanic properties.

Afterwards, the self-cementing coal fly ash was added at rates of 2.5%, 5.0%, 7.5%, 10.0%, 12.5% and 15.0% (by dry weight of soil) to the different soils and their consistency properties and moisture-density relationships investigated. Furthermore, samples were prepared for the unsoaked California Bearing Ratio (CBR) tests which

were carried out after curing for three days.

3. Results and Discussion

In most systems of soil classification, the silt and clay grain sizes comprise the fraction passing the 0.075 mm sieve size, while the sand fraction comprises grains passing the 2.36 mm sieve size and retained on the 0.075 mm sieve size. It is evident therefore, from Table 1, that though the sand fraction is predominant in the particle size distribution of all the soils sampled in the study, the clay fraction is also significant (greater than 30%). With the plastic limits relatively high (between 37 and 42%) and the plasticity indices from 14 to 17%, the soils are classified as A-6, A-7-5 and A-2-6, respectively, according to the AASHTO classification system. According to the Unified Soil Classification system, Soils A and C belong to SC group (silty sand with medium plasticity), while Soil B belongs to the SM group (clayey sand with medium plasticity). Soils A and C plot below the A-line in the Casagrande plasticity chart, while Soil C plots above it. According to both classification systems, the general rating of all the soils as a road foundation was "fair to poor", suggesting that some modification through stabilization would be necessary.

The results of the addition of varying contents by weight of coal fly ash to the different soil samples are presented in Tables 2a to 2c, and the average results in Table 2d.

It was observed that increasing the percentages of coal fly ash content from 0 to 15% resulted in marginal decreases in the liquid limits (from an average of about 39.0% to an average of about 33.3% when comparing the values at 0% and 12.5% coal fly ash contents) and marginal increases in the plastic limits of the soils. With this, there was a noticeable decrease in the plasticity indices (from an average of about 15.3% to an average of about 9.3% when comparing the values at 0% and 12.5% coal fly ash contents).

It was also observed that with increasing coal fly ash contents, the optimum moisture contents decreased (from an average of about 15.8% to an average of about 9.7% when comparing the values at 0% and 12.5% coal fly ash contents) while the maximum dry densities increased (from an average of about 1920 kg/m^3 to an average of about 2180 kg/m^3 when comparing the values at 0% and 12.5% coal fly ash contents). Similarly, the unsoaked CBR of the different soils increased with increasing coal fly ash content (from an average of about 20.0% to an average of about 53.3% when comparing the values at 0% and 12.5% coal fly ash contents).

These improvement in the natural and mechanical characteristics of lateritic soil stabilized with coal fly ash is in line with those observed in other types of soil stabilized with coal fly ash (Brown *et al.*, 1991; Beeghly, 2003; Mackiewicz and Ferguson, 2005; White *et al.*, 2005; Eskioglou and Oikonomou, 2008; Brooks, 2009; Li *et al.*, 2009; Rifa'i *et al.*, 2009).

For the plasticity indices, it was observed that the values dropped sharply from 0% content until about 10% to 12.5% content when the value seemed to remain constant. The final value of the plasticity indices (around 9 to 10%) from the initial high values (between 14 and 17%) has placed the modified soils, according to AASHTO criteria, as suitable materials for subgrade and base course construction.

Similarly, the rate of decrease in the values of the optimum moisture content and increase in the maximum dry densities and CBR values seemed to peter out around coal fly ash contents of 12.5%. With all the above, it can be reasonably concluded that an overall optimum coal fly ash content by weight for the stabilization of lateritic soils is 12.5%. This is comparable to values recommended by other investigators, though for different soil types. White *et al.* (2005) recommended addition rates of 10% to 20% (by dry weight of soil) for Iowa self-cementing fly ashes for effective stabilization of fine-grained Iowa soils for earthwork and paving operations. Mackiewicz and Ferguson (2005) stated that most fly ash stabilization applications require fly ash contents ranging from 12 to 15% (dry weight basis). Eskioglou and Oikonomou (2008) opined that, when sand-gravels are stabilized beyond 10% of fly ash, the strength is not considerably increased and stabilization has nothing more to offer.

4. Conclusion and Recommendations

From this study, the following conclusions and recommendations can be drawn:

- For lateritic soils, addition of about 12.5% (by dry weight of soil) of self-cementing coal fly ash provides the most effective stabilization when all the properties are considered together.
- The mixture of coal fly ash with lateritic soils improves the plasticity and mechanical properties of the soil, as expressed by a reduction in the liquid limit and the plasticity index.
- With regard to the influence of self-cementing fly ash on density and compaction, test results show that fly ash increases the compacted dry density and reduces the optimum moisture content of lateritic soils.
- Coal fly ash stabilization increases the CBR of lateritic soils. For the soils tested, the CBR values

increased from about 20% to about 56% for 12.5% coal fly ash addition.

- Usage of fly ash for stabilization offers an effective way of reducing the burden of storage and disposal of the waste by-products of coal combustion and the attendant environmental and health hazards.
- Economically, coal fly ash stabilization is much cheaper than stabilization with the conventional materials. Mackiewicz and Ferguson (2005) stated that fly ash treatment is generally more economical than the lime and cement alternatives even when larger quantities of ash have to be added to achieve the stabilization required.

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Table 1. Physical Properties Of Soil Samples

PHYSICAL PROPERTY		**SOIL A**	**SOIL B**	**SOIL C**
Description		Red-brown sandy clay	Red-brown clayey sand	Light-brown sandy clay
Grain size distribution (percentage passing sieve sizes):	9.50 mm	100.0	100.0	100.0
	4.75 mm	95.3	95.2	98.1
	2.36 mm	93.3	93.4	94.0
	1.18 mm	90.0	88.4	85.4
	0.600 mm	79.1	80.1	76.2
	0.425 mm	68.6	70.2	62.1
	0.300 mm	59.7	61.4	54.6
	0.150 mm	48.2	43.8	43.5
	0.075 mm	40.1	40.5	31.4
Gravel content, %		6.7	6.6	6.0
Sand content, %		53.2	48.9	62.6
Fines content, %		40.1	40.5	31.4
Specific Gravity		2.70	2.86	2.88
Natural Moisture Content, %		18.8	20.0	15.9
Liquid Limit, %		38.0	42.0	37.0
Plastic Limit, %		21.0	28.0	22.0
Plasticity Index, %		17.0	14.0	15.0
Optimum Moisture Content (Standard Proctor), %		18.1	14.4	15.0
Maximum Dry Density (Standard Proctor), kg/m^3		1840	1960	1960
AASHTO Classification		A-6	A-7-5	A-2-6
Group Index		3	2	1
Universal Soil Classification		SC	MI	SC

Table 2a. Results of the stabilization of soil a with coal fly ash

SOIL PROPERTY	**COAL FLY ASH CONTENT, % BY WEIGHT**						
	0	**2.5**	**5.0**	**7.5**	**10.0**	**12.5**	**15.0**
Liquid Limit, %	38.0	37.0	35.0	36.0	32.0	37.0	31.0
Plastic Limit, %	21.0	23.0	24.0	26.0	23.0	27.0	22.0
Plasticity Index, %	17.0	14.0	11.0	10.0	9.0	10.0	9.0
Optimum Moisture Content (Standard Proctor), %	18.1	16.6	15.1	11.4	10.7	10.1	10.1
Maximum Dry Density (Standard Proctor), kg/m^3	1840	1960	1970	2080	2130	2150	2180
Unsoaked CBR, %	23	34	38	40	48	56	61

Table 2b. Results of the stabilization of soil b with coal fly ash

SOIL PROPERTY	COAL FLY ASH CONTENT, % BY WEIGHT						
	0	**2.5**	**5.0**	**7.5**	**10.0**	**12.5**	**15.0**
Liquid Limit, %	42.0	47.0	32.0	35.0	32.0	31.0	32.0
Plastic Limit, %	28.0	34.0	19.0	24.0	22.0	22.0	24.0
Plasticity Index, %	14.0	13.0	13.0	11.0	10.0	9.0	8.0
Optimum Moisture Content (Standard Proctor), %	14.4	12.0	11.4	10.5	10.3	9.9	8.7
Maximum Dry Density (Standard Proctor), kg/m^3	1960	2070	2120	2140	2160	2190	2220
Unsoaked CBR, %	18	20	31	32	35	45	48

Table 2c. Results of the stabilization of soil c with coal fly ash

SOIL PROPERTY	COAL FLY ASH CONTENT, % BY WEIGHT						
	0	**2.5**	**5.0**	**7.5**	**10.0**	**12.5**	**15.0**
Liquid Limit, %	37.0	42.0	37.0	34.0	34.0	32.0	31.0
Plastic Limit, %	22.0	28.0	25.0	23.0	24.0	23.0	22.0
Plasticity Index, %	15.0	14.0	12.0	11.0	10.0	9.0	9.0
Optimum Moisture Content (Standard Proctor), %	15.0	12.5	11.5	10.2	10.2	9.0	8.8
Maximum Dry Density (Standard Proctor), kg/m^3	1960	2080	2120	2140	2180	2190	2210
Unsoaked CBR, %	19	36	39	41	48	58	57

Table 2d. Average results of the stabilization of soils a, b and c with coal fly ash

SOIL PROPERTY	COAL FLY ASH CONTENT, % BY WEIGHT						
	0	**2.5**	**5.0**	**7.5**	**10.0**	**12.5**	**15.0**
Liquid Limit, %	39.0	42.0	34.7	35.0	32.7	33.3	31.3
Plastic Limit, %	23.7	28.3	22.7	24.3	23.0	24.0	22.7
Plasticity Index, %	15.3	13.7	12.0	10.7	9.7	9.3	8.7
Optimum Moisture Content (Standard Proctor), %	15.8	13.7	12.7	10.7	10.4	9.7	9.2
Maximum Dry Density (Standard Proctor), kg/m^3	1920.0	2036.7	2070.0	2120.0	2156.7	2176.7	2203.3
Unsoaked CBR, %	20.0	30.0	36.0	37.7	43.7	53.0	55.3

ISSN 1913-1844 E-ISSN 1913-1852

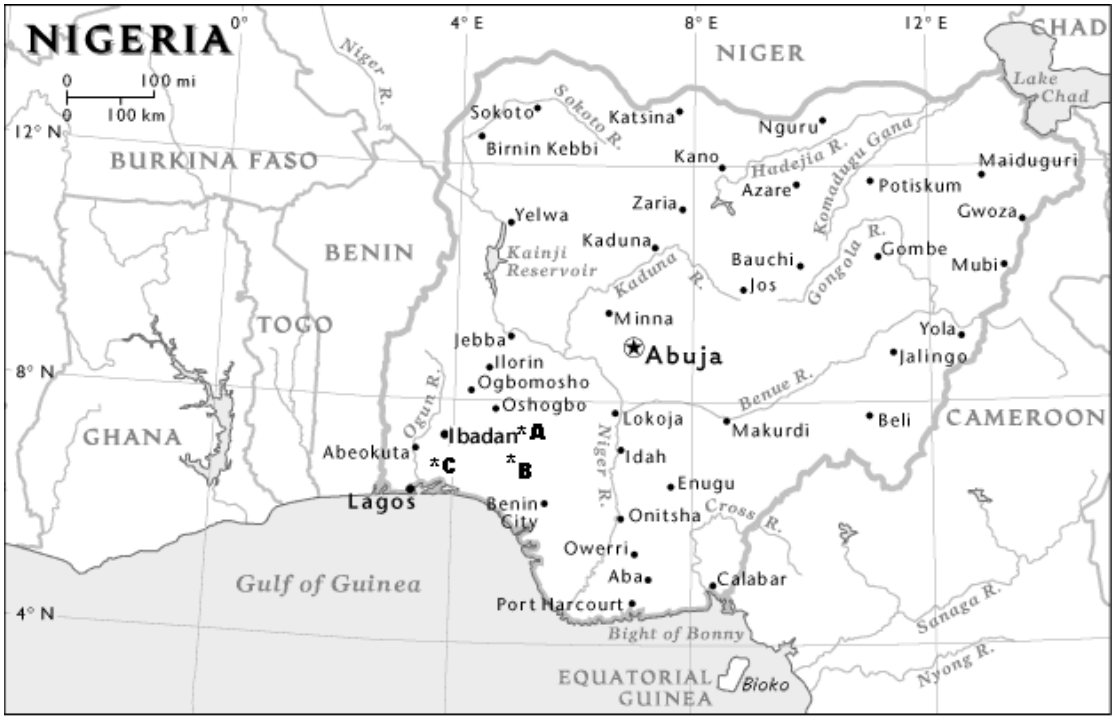

Figure 1. Map showing the locations of soil sample collection (adapted from National Geographic Society, 1998)